Machinery Messages

Part 2

Using Full Spectrum Plots

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Part 1 of this article was included in the December 1993 Orbit [Ref 1].

Synopsis of Part 1

A full spectrum has the same relationship to a "standard" spectrum in the frequency domain as an orbit has to a timebase plot in the time domain. Spectrum and timebase plots use data from a single transducer. Full spectra and orbits require data from two orthogonal transducers and, therefore, can provide information on the ellipticity of the orbit and the direction of vibration. The amplitude relationship between the forward vibration and reverse vibration components of a full spectrum can be used to determine the ellipticity and direction of the orbit. When making a machinery diagnostic analysis, it is important to remember that the machine is doing what the orbit shows it is doing. The forward and reverse vibration components are solutions from the fast Fourier transform computation which generate the same orbit.

Rubs

Rubs are classified as secondary malfunctions. They never happen all by themselves, but are always a result of something else. Clearances can be too tight or too loose. Other phenomena, such as excessive or improper preloads (gravity, internal or external misalignment, gear mesh, fluid flow, etc.), poorly balanced rotor, deformed casing, etc., can also cause rubs. Rubs are often difficult to diagnose because the machine response can be a chaotic function of several parameters. A very slight change in any of the parameters can produce an extremely different result. There are many things to consider. Is the action wiping, or impact/

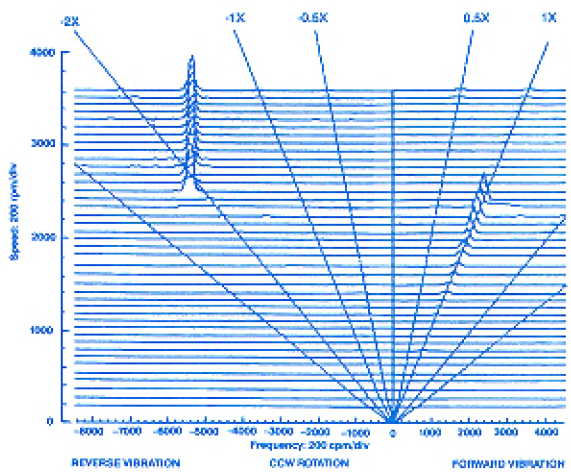


Figure 1
Full annular rub runup

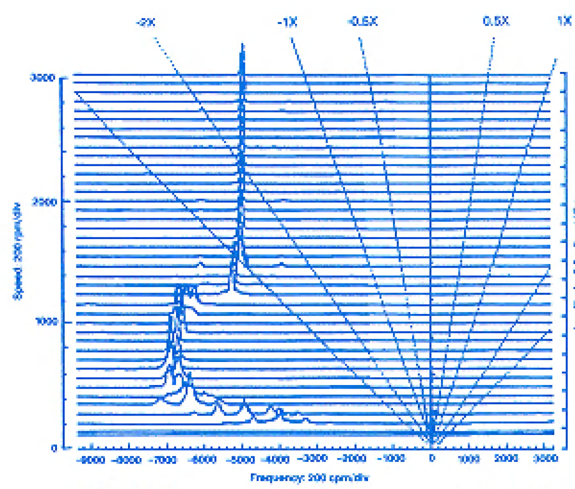


Figure 2
Full annular rub rundown

rebound? Is it heavy or light? Is it lubricated or dry? Is it partial or full annular? If it is full annular, is it forward or reverse? Is it normal-tight (normal stiffness which gets stiffer during the rub) or normal-loose (normal stiffness which gets softer)? What is the machine speed relative to the balance resonance frequency (below, above, more than twice, etc.)?

For a comprehensive diagnosis of a rub condition, the wide variety of possible machine responses to the wide variety of different rubs basically means that a wide variety of techniques and tools will be necessary. Orbit plots, shaft centerline position plots, Bode and polar plots, and spectrum/full spectrum plots should *all* be used. Since full spectrum plots make reverse vibration components easy to see, they can be useful in diagnosing high-friction type rubs which generate reverse vibration components. Figures 1 & 2 are examples of full spectrum cascade plots.

Full spectrum cascade plots of a full annular rub with reverse precession are shown for both startup (Figure 1) and shutdown (Figure 2) conditions. The orbit of a full annular rub is generally circular and is as large as the bearing or seal clearance. The frequency of vibration is a modified natural frequency, which is higher during the rub due to increased stiffness when the shaft contacts the bearing or seal wall, and is independent of rotative speed. The circular shape and direction of the orbits can be confirmed from these full spectrum cascade plots by observing that when the vibration components exist in the forward direction, there are no significant reverse components, and vice versa. The modified natural frequency of the system is also easily determined. With just these two plots, however, there is insufficient information to determine the non-rub natural frequency or to verify the bearing and seal clearances.

Although the reverse precession full annular rub illustrated here is extremely rare, it is also extremely destructive. The competent machinery diagnostician should be able to quickly and accurately recognize this rub condition. Don't assume that all reverse precession components are bad, or that reverse precession components are always due to rubs. Neither of these statements is true. Please refer to the discussion on split criticals (resonance) later in this article.

Preloads and misalignment

A preload is a unidirectional, steady state force acting on a rotor system. The most common preload is gravity. Other sources of preloads are internal and external misalignment, process and fluidic forces, bearing geometry, pipe strain, and differential (thermal) expansion. The presence of measurable signal characteristics is dependent on machinery type, the severity of the preload, process conditions, and the relationship between operating speed and resonance frequencies. It is possible that no definitive signal characteristics will be measurable. Applying a preload to a shaft will cause the shaft to change its eccentricity position within the bearing clearance, which will in turn cause the stiffness of the system to change. Increased stiffness may alter a machine's stability, and can often lead to a lower vibration level. Although lower vibration levels are usually thought to be good, low vibration levels aren't good if the cause is severe misalignment. High radial preloads can cause the shaft to operate in a nonlinear stiffness region, which will generate harmonic components of the vibration signal; a 2X component is common. (continues on page 14)

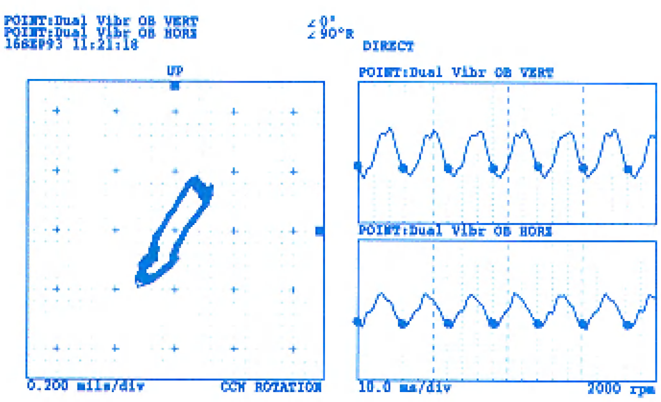


Figure 3
Orbit/Timebase plot, preload

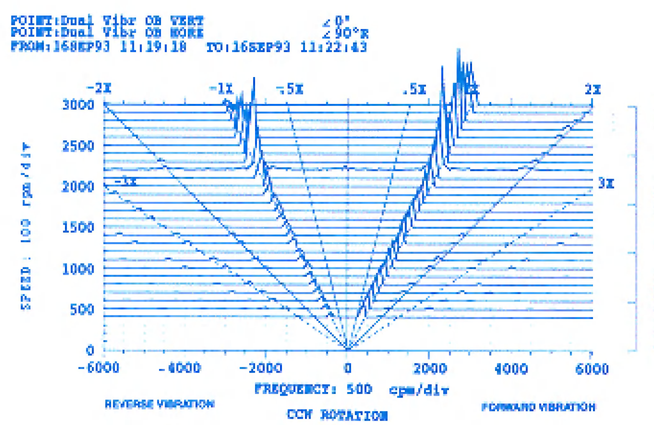


Figure 4
Full spectrum cascade plot, preload

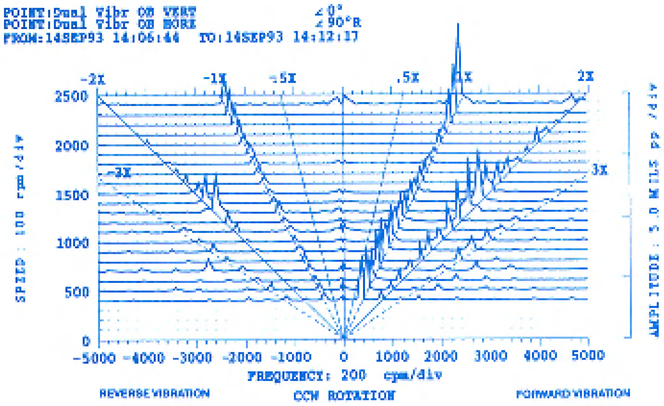


Figure 5
Full spectrum cascade, shaft crack, startup

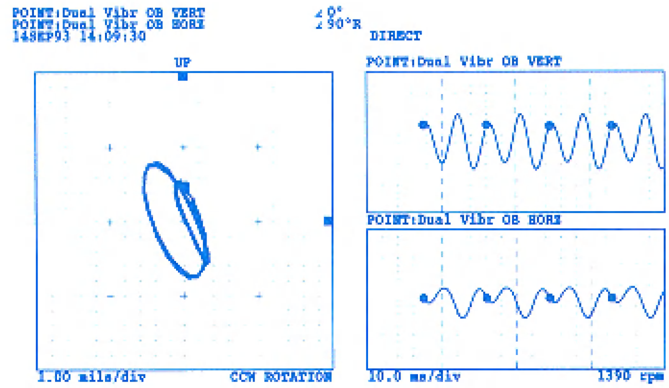


Figure 6
Direct orbit, shaft crack, 1390 rpm

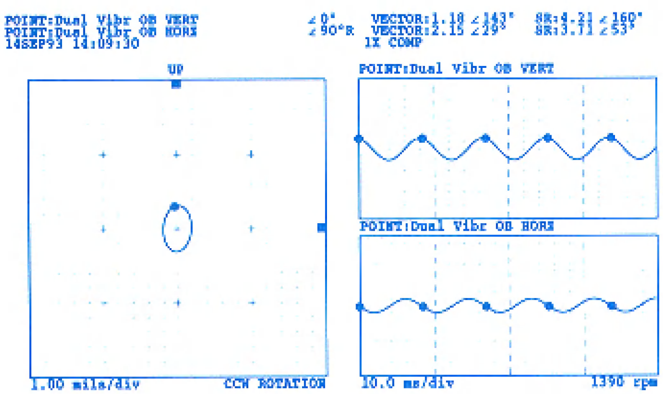


Figure 7
1X component - orbit, shaft crack, 1390 rpm

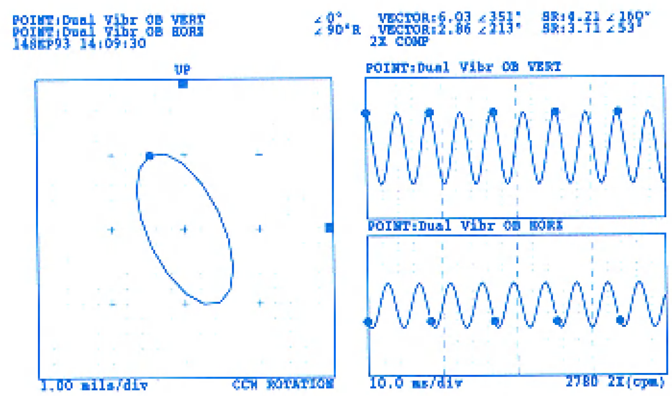


Figure 8
2X component - orbit, shaft crack, 1390 rpm

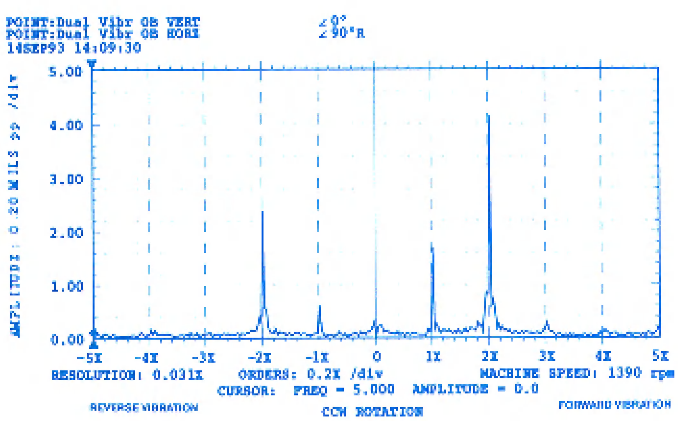


Figure 9
Full spectrum - shaft crack, 1390 rpm

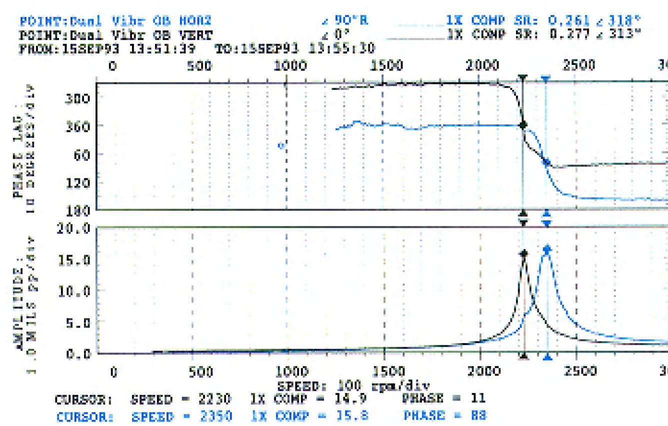


Figure 10
Bode plot, split critical

From a machinery diagnostics point of view, the primary plots used for preload investigations are orbits and shaft centerline position. Full spectrum plots are best used to confirm information obtained from other plots when dealing with suspected preload problems. Figure 3 shows a forward, elliptical, primarily 1X orbit of a preloaded shaft. This is confirmed by the full spectrum cascade plot (Figure 4). Notice that the full spectrum cascade plot reveals the same general pattern (i.e., forward, elliptical, and primarily 1X) for the entire machine startup, for this particular transducer.

Shaft Crack

Asymmetric stiffness in a rotor, i.e., the rotor is stiffer in one lateral direction than it is in the perpendicular direction, can result from geometric causes (keyways, non-circular cross-sections, etc.), manufacturing or maintenance problems (poor or improper press fits or shrink fits), or machine malfunction (shaft crack). When a (horizontal) rotor with an asymmetric stiffness makes one revolution with respect to a given point, such as a vertical displacement probe, the stiffness will vary from stiff to soft to stiff to soft. In the presence of a lateral preload (e.g. gravity), this variation in stiffness causes the rotor to deflect a small amount, large amount, small amount, and large amount, respectively, during the one revolution. The two cycles of displacement which occur over the one revolution, of course, describe a 2X signal. This 2X component is linear (assuming stiffnesses do not change), forward, circular, and may be much larger than the 1X component (especially at 2X resonance) [Ref 2]. Approximately 75% of the time, only 1X behavior is exhibited at operating speed.

From a machinery diagnostic point of view, we look for shaft cracks by applying the first and second rules of shaft cracks. Cascade, full spectrum cascade, orbit, polar, acceptance region and Amplitude and Phase versus Time (APHT) plots are the primary formats used for shaft crack detection.

1st Rule of Cracks: *If a shaft is cracked, it is almost certainly bowed.*

*(**Note:** Applying the 1st Rule does not require full spectrum plots, but is included here for completeness.)*

1. Acceptance region and APHT plots highlight unexpected amplitude or phase changes in both the 1X and 2X vectors.
2. Rotor bow is one of the components of a 1X slow roll vector, along with mechanical runout and electrical runout. Over time, when measured under identical circumstances, 1X slow roll vectors should not change value without reason. Keep a log of 1X slow roll vectors for each machine. All significant changes must be investigated and a shaft crack should be considered.

2nd Rule of Cracks: *A rotor with an asymmetric stiffness and a radial sideload, rotating at a speed near half of any resonance frequency, may experience high 2X vibration amplitude and 2X phase shift.*

1. When operating near half of any resonance frequency, and there is a 2X excitation force, the resonance will be excited. The full spectrum cascade plot (Figure 5) clearly shows a peak in the 2X amplitude at about 1300-1400 rpm. Note that this machine also has both 3X and 4X components, and there is a peak in the 3X amplitude at about 900 rpm, and a peak in the 4X amplitude at about 700 rpm. The first balance

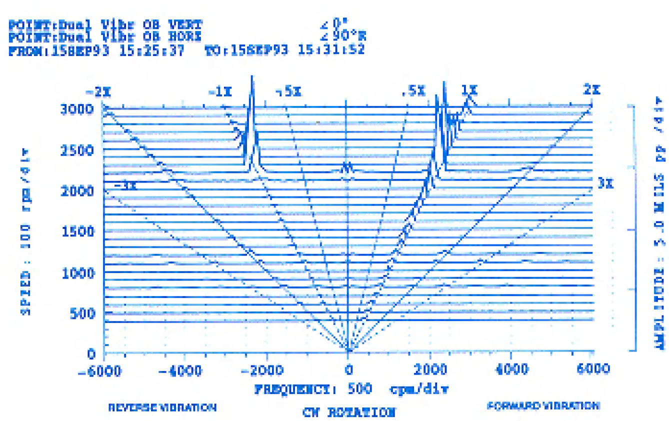
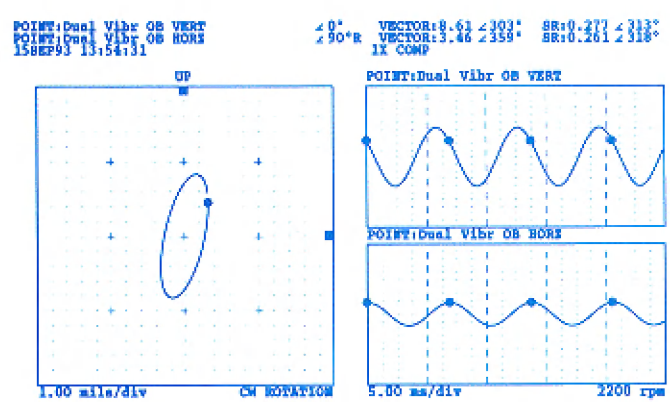


Figure 11
Full spectrum cascade, split critical



Figures 12
1X Orbit/Timebase for 2200 rpm

resonance of this machine is approximately 2700 rpm.

2. When operating at 1390 rpm, i.e., near half of the first balance resonance frequency, the direct orbit (Figure 6), the 1X slow roll compensated orbit (Figure 7), the 2X slow roll compensated orbit (Figure 8), and the full spectrum plot (Figure 9) show the following:
   a. The 1X component is forward and slightly elliptical.
   b. The 2X component is forward, more elliptical, and larger than the 1X component.
   c. The internal loop in the direct orbit is a characteristic for signals containing two vibration components with the same direction of precession [Ref 2].

Split Criticals

Fundamental synchronous rotor response teaches us that the resonance frequency of a simple rotor is:

$\omega_{res} = \sqrt{K/M}$ where ω = resonance frequency

K = stiffness

M = mass

When a machine is stiffer in one direction than it is in another direction, this relationship tells us that we can expect the resonance frequency of the machine to be higher in the stiffer direction and lower in the softer direction. This, in fact, occurs with virtually every machine. The system stiffness, which includes contributions from bearing supports, foundation, and piping, is rarely the same in every direction.

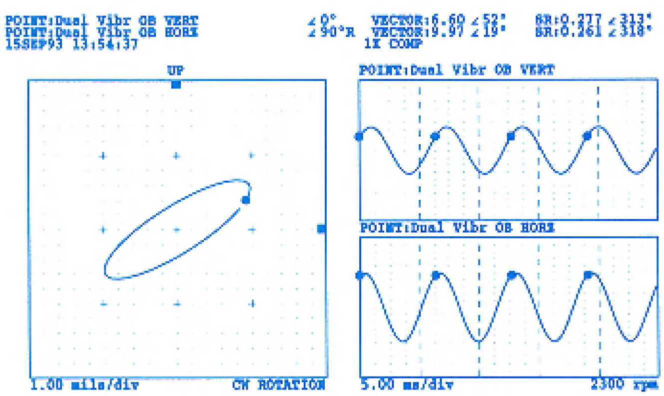
Figure 10 shows Bode plots for two orthogonal (0° and 90° Right) displacement transducers which were located at the outboard bearing of a machine with a clockwise rotating shaft. The first balance resonance speed (1st critical) in the vertical direction is 2230 rpm, and the first balance resonance speed (1st critical) in the horizontal direction is 2350 rpm.

Using the phase lag portions of the Bode plots, compare the phase of the vibration signals: below 2230 rpm and above 2350 rpm, the precession is forward, i.e., the vertical vibration leads the horizontal vibration. Between 2230 rpm and 2350 rpm, however, the precession is reverse, i.e., the horizontal vibration leads the vertical vibration. Remember that this reverse precession isn't bad, and there is no malfunction. The reverse precession is due to the machine's response to the asymmetric stiffness, and is a very normal occurrence.

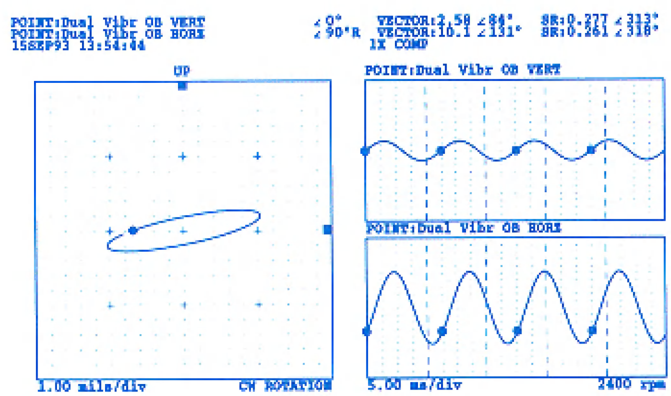
The full spectrum cascade plot (Figure 11) and 1X orbit/timebase plots (Figures 12, 13, and 14) are used to confirm this analysis. The 1X vibration is forward (the forward 1X vibration component is larger than the reverse 1X vibration component) for the entire startup except for a brief period of reverse vibration around 2300 rpm. Peaks in the forward 1X vibration are seen at 2200 rpm and 2400 rpm, corresponding to the vertical and horizontal split critical frequencies, and a peak in the reverse 1X vibration is seen at 2300 rpm. ■

References

1. Southwick, D., "Using Full Spectrum Plots," Orbit, Volume 14, No. 4, December, 1993.
2. Muszynska, A., "Misalignment and Shaft Crack-Related Phase Relationships for 1X and 2X Vibration Components of Rotor Responses," Orbit, Volume 10, No. 2, September 1989.



Figures 13
1X Orbit/Timebase for 2300 rpm



Figures 14
1X Orbit/Timebase for 2400 rpm